# Neutrinoless double $\beta$ decays of the $t$ quark and other effects of heavy Majorana neutrinos

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# Outline

- I: Motivation to study heavy Majorana neutrinos and top quarks.

- II: Majorana neutrinos and lepton–number–violating signals in $t$–quark and $W$–boson rare decays, based on: S. Bar-Shalom, N.G. Deshpande, GE, J.Jiang and A. Soni, plb 643, 342 (2008).

- III: Enter $H^+$ and $H^-$:
Charged Higgs–boson effects in the production and decay of a heavy Majorana neutrino at the LHC, based on: S. Bar-Shalom, GE, T. Han and A. Soni, prd77, 115019 (2008).

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I Motivation to study heavy Majorana neutrinos and top quarks.

The discovery of neutrino oscillations implies that neutrinos have mass. Thus indicating that there is New Physics (NP) beyond the Standard Model (SM). A simple way to consistently include sub-eV massive Majorana neutrinos in the SM is to add superheavy right-handed neutrinos with GUT-scale masses and to rely on the seesaw mechanism which yields the desired light neutrinos mass scale:

$$m_\nu \sim M_{EW}^2 / M_{GUT} \sim 10^{-2} eV.$$

This seesaw mechanism links neutrino masses with NP at the GUT scale and raises the possibility that neutrinos will be of the Majorana type, where they are the antiparticles of themselves.

The mechanism through which neutrinos acquire mass is yet unknown and might be different from the seesaw one. We take a purely phenomenological approach in which the masses of the heavy neutrinos are not predetermined by a specific model.

WHY TOPS ?

Most of us believe (or have we convinced ourselves?) that something new is lurking over there, at about the scale of EW symmetry breaking, which is around 250 GeV.

The top quark at 172.6 GeV is the quark closest to that scale and is therefore the most sensitive to NP.

E.g., various models of NP may lead to FCNC of top (such as $t \to cH^0$ which are 10 orders of magnitude larger than their SM values, or $cg \to t$.)

## II: Majorana neutrinos and lepton–number–violating signals in $t$–quark and $W$–boson rare decays.

The well–known case which proceeds only if the light neutrino is Majorana, and is Lepton Number Violating (LNV), with $\Delta L = 2$ is the neutrinoless double beta decay

$$(A, Z) \to (A, Z + 2) + e^- + e^-,$$

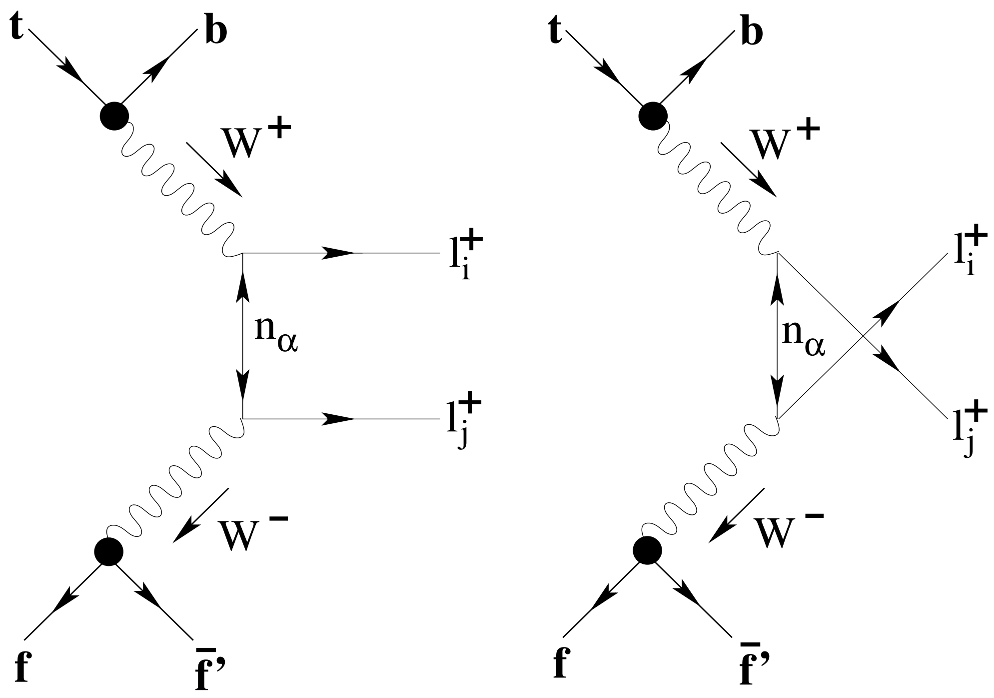
which has not been observed (?) and it suffers from nuclear effects. Nevertheless, it produces useful limits.

Also interesting are the $\Delta L = 2$ LNV processes in various high-energy collisions such as $e^- \, e^- \to W^- \, W^-$ and in rare charged meson and lepton decays.

We explored two additional LNV decay channels of the real top-quark and of the real W-boson, to like-sign lepton pairs:

$$t \to b\ell_i^+ \ell_j^+ W^-,$$

$$W^+ \to \ell_i^+ \ell_j^+ f \bar{f}'.$$




These decays are induced by heavy Majorana neutrino exchanges and may, therefore, serve as important tests of the neutrino sector and as a possible evidence for the existence of Majorana-type heavy neutrinos with masses at the EW scale.

Both decays emanate from the same "kernel" process:

$$W^{\pm}W^{\pm} \to \ell_i^{\pm}\ell_j^{\pm},$$

with an exchange of a Majorana neutrino. This is the same kernel that induces $0\nu\ 2\beta$ in nuclei. However, in contrast to the the nuclear case, the $0\nu\ 2\beta$ decays of $t$ and $W$ are dominated by the exchanges of heavy (EW scale) neutrinos instead of sub-eV neutrinos.

For the $t$ case the top-quark decays to an on-shell $W$-boson with a "wrong" charge, as compared with "right" charge $W$-boson in the main decay $t \to bW^+$. The above "weird" $t$ and $W$ decays, originates from:

$$\mathcal{L} = -\frac{g}{2\sqrt{2}} B_{in} W_\mu^- \ell_i \gamma^\mu (1-\gamma_5) n_\alpha \ , + H.c.$$

$\alpha = 1-6$: 6 Majorana neutrino states, 3 light and 3 heavy. $B_{in}$: $3 \times 6$ matrix, $B_{in} \equiv \sum_{k=1}^{3} V_{ki}^L U_{kn}^*$ where $V^L$ is the $3 \times 3$ unitary mixing matrix of the left-handed charged leptons and $U$ is the $6 \times 6$ unitary mixing matrix in the neutrino sector.

The possibility of non-seesaw realizations or internal symmetries in the neutrino sector, that decouple the heavy-to-light neutrino mixing from the neutrino masses, cannot be excluded. In a model independent approach, the couplings are bounded by experimental constraints.

Assume: a single heavy neutrino $N$ dominates. The limits on its couplings to the charged leptons is expressed in terms of $\Omega_{\ell\ell'} \equiv B_{\ell N} B_{\ell' N}$.

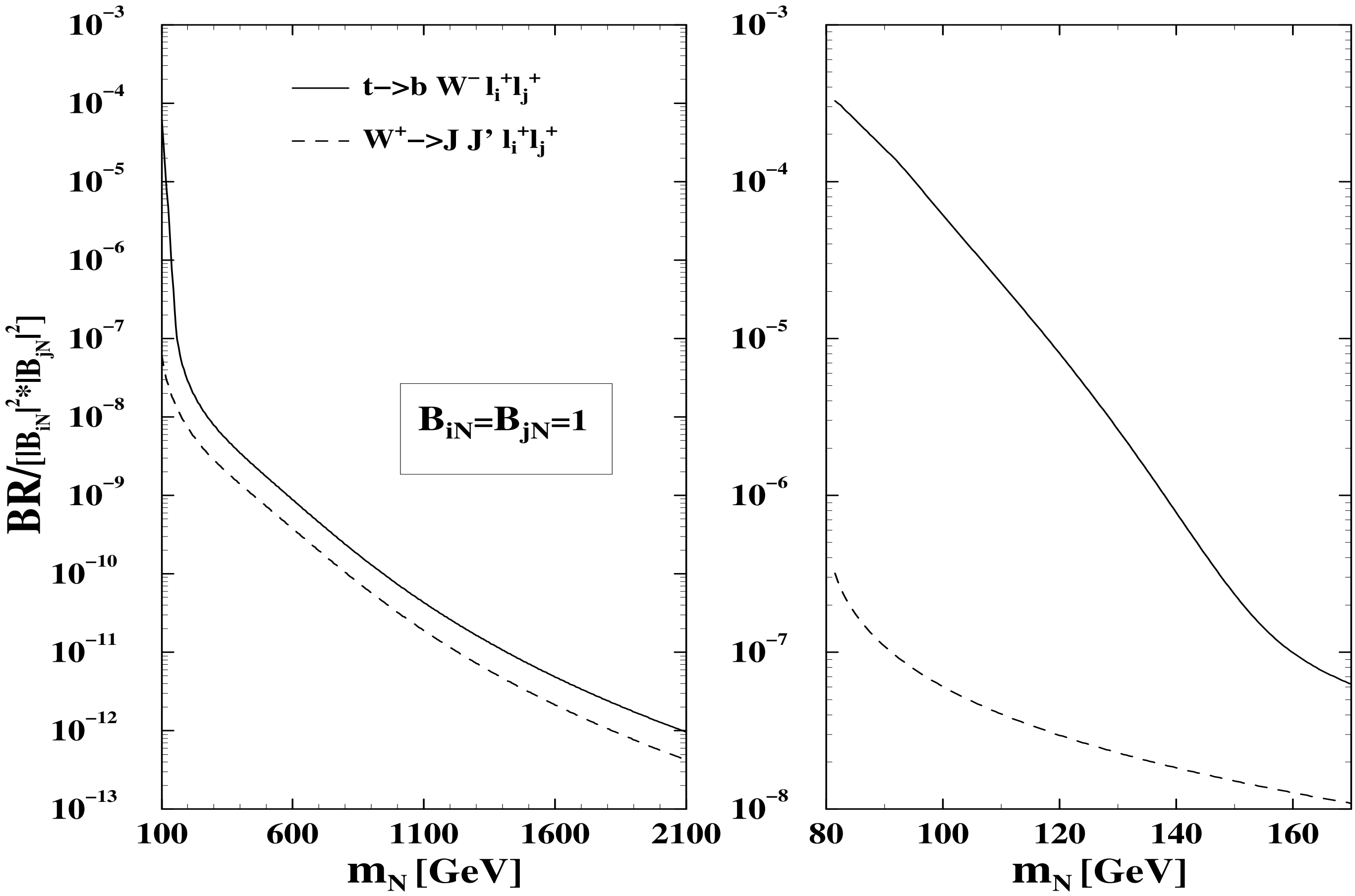
Limits on its flavor-diagonal couplings come from precision electroweak data, at 90% CL, are:

$$\Omega_{ee} \leq 0.012 \ , \ \Omega_{\mu\mu} \leq 0.0096 \ , \ \Omega_{\tau\tau} \leq 0.016 \ ,$$

and on flavor-changing couplings, come from limits on rare flavor–violating lepton decays:

$$|\Omega_{e\mu}| \leq 0.0001 \ , \ |\Omega_{e\tau}| \leq 0.02 \ , \ |\Omega_{\mu\tau}| \leq 0.02 \ .$$

The results of the calculations are depicted in the following figures:




The BR's scaled by the mixing parameters, $B_{iN} = B_{jN} = 1$, vs the Majorana neutrino mass, $m_N$. We see that, for both decays, a sizable BR can arise only for $m_N$ around 100 GeV

$$BR(t \to bW^- \ell_i^+ \ell^+) \sim 10^{-4}$$

$$BR(W^+ \to J\bar{J}' \ell_i^+ \ell_j^+) \sim 10^{-7}$$

For a more realistic BR's we use the bounds on the couplings. For the $W$-boson decay, the largest BR is of order of $10^{-10}$. This is too small to be observed at the Large Hadron Collider (LHC), where about $10^9 - 10^{10}$ inclusive on-shell $W$'s are expected to be produced through $pp \to W + X$, at an integrated luminosity of $\mathcal{O}(100)$ fb$^{-1}$.

However, for more energetic off-shell $W$-bosons, produced (at hadron colliders) in the s-channel via $ud$ fusion, $ud \to W^*$, the sensitivity to the heavy Majorana exchanges can be significantly enhanced. Indeed, it was shown that s-channel $W^*$ can "decay" $W^* \to J\bar{J}' \ell_i^\pm \ell_j^\pm$, by first decaying to an on-shell Majorana neutrino $W^* \to \ell N$, followed by $N \to \ell W \to \ell J \bar{J}'$.

The "decay" of a $W^*$ to an intermediate on-shell $N$, substantially enhances the cross-section and makes this process, *i.e.*, $ud \to W^* \to J\bar{J}'\ell_i^\pm \ell_j^\pm$, easily accessible at the LHC.

In the case of the top-quark decay $t \to bW^-\ell_i^+\ell_j^+$, taking $m_N \sim 100$ GeV and using the limits we discussed, the BR's for the various $\ell_i^+\ell_j^+$ channels are given in the following table:

| | $BR(t \to bW^-\ell_i^+\ell_j^+) \times 10^6$ | | | | | |
|---|---|---|---|---|---|---|
| $\ell_i\ell_j =$ | $ee$ | $\mu\mu$ | $\tau\tau$ | $e\mu$ | $e\tau$ | $\mu\tau$ |
| $m_N = 90$ GeV | 1.4 | 1.1 | 1.9 | $1.1 \cdot 10^{-4}$ | 1.6 | 1.4 |
| $m_N = 100$ GeV | 0.6 | 0.5 | 0.8 | $0.4 \cdot 10^{-4}$ | 0.7 | 0.6 |

The cross-section for $t\bar{t}$ production at the LHC is $\sim$ 850 pb, yielding about $10^8$ $t\bar{t}$ pairs at an integrated luminosity of $\mathcal{O}(100)$ fb$^{-1}$. Thus, a $BR(t \to bW^-\ell_i^+\ell_j^+) \sim 10^{-6}$ that can arise in most $\ell_i^+\ell_j^+$ channels (see Table above) should be accessible at the LHC. In particular, the flavor-changing decay channels $t \to bW^-e\tau$ and $t \to bW^-\mu\tau$ seem to be the most promising ones (in spite of the low $\tau$ detection efficiency) as the they are expected to be the cleanest with respect to background.

Note that a Majorana exchange is not necessarily the only mechanism leading to $\Delta L = 2$ processes. One can envisage, for instance, a situation in which another type of new physics contributes together with the heavy Majorana exchange. Viable examples are R-parity violating supersymmetry, or leptoquark exchange. In the (rather contrived) cases like these it is in principle possible to obtain destructive interference between the different mechanisms, thus evading the limits on the couplings considered here. Therefore, the rather sizable branching ratios, obtained for $\mathcal{O}(1)$ mixing angles cannot be excluded.

Finally, it should also be noted that there are some discussions about a Super LHC (SLHC) in which the luminosity of the LHC would increase by about factor of 10. There is also some mention of an energy upgrade from $\sqrt{s} = 14$ TeV to 25-28 TeV, which may require a new machine.

To summarize this part: We have discussed the $\Delta L = 2$ decays of the top-quark and of the $W$-boson, where both are mediated only by a heavy Majorana neutrino $N$. Our main results appear in the figure of BR's and in the table and are significant for the top-quark case, especially if one can avert the rather severe constraints emanating from neutrinoless double $\beta$ decay.

## III: Enter $H^+$ and $H^-$: Charged Higgs-boson effects in the production and decay of a heavy Majorana neutrino at the LHC.

We considered a new interaction between a heavy Majorana neutrino ($N$) and a charged Higgs boson ($H^\pm$), and show that it can have drastic implications on LNV signal of same-sign dileptons at the LHC. The LNV signal of heavy Majorana neutrinos previously considered at the LHC, $pp \to \ell^+ N \to \ell^+ \ell^+ W^-$, may be overwhelmed by $pp \to \ell^+ N \to \ell^+ \ell^+ H^-$. With the subsequent decays $H^- \to \bar{t} b$ or $H^- \to W^- H^0$, the heavy Majorana neutrino production leads to the spectacular events of $\ell^+ \ell^+ \; b\bar{b}$+2 jets. We also explore the case $m_N < m_{H^+}$, where the decay $H^+ \to \ell^+ N$ can become the dominant $N$-production mechanism at the LHC. In particular, we show that the process $g\bar{b} \to \bar{t} H^+$ followed by $t \to \bar{b} W^-$ and $H^+ \to \ell^+ N \to \ell^+ \ell^+ W^-$ could lead to another type of spectacular events of $\ell^+ \ell^+ \; b$+4 jets.

## IV: Summary

WILL THE LHC BE ALL IN ONE: HIGGS AND TOP QUARK FACTORY AND TEACH US ABOUT LNV? LET US HOPE SO.